Accelerated Insertion of Materials - Composites

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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **2001**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Accelerated Insertion of Materials Composites, Presented at the DARPA Workshop, Annapolis, August 27-28, 2001**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Boeing**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**70**	

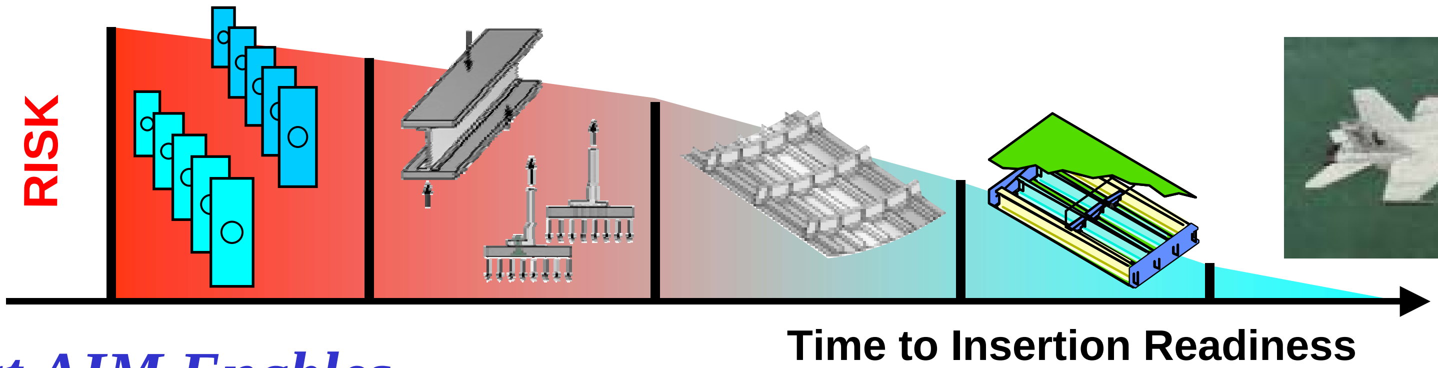
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Program Overview - Gail Hahn
  - Accelerated Insertion of Materials – Composites
  - Composite Materials Insertion Process and Issues
  - Issues for this audience

- Uncertainty - Issues and Challenges - Raj Rajagopal
  - Definition
  - Composite Materials Domain
  - Technologies Under Consideration
  - Challenges

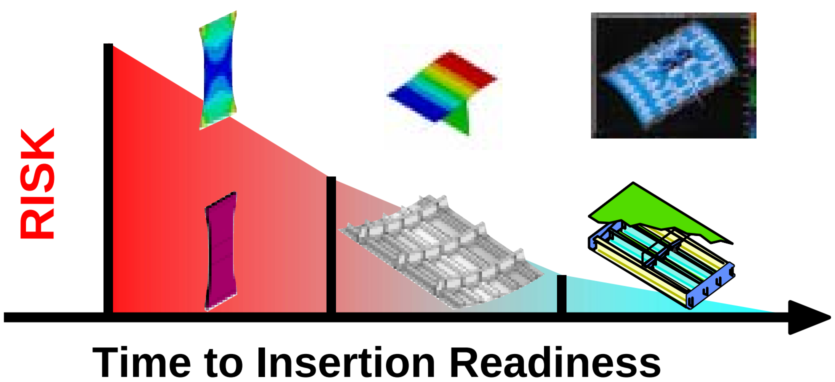
Accelerated Insertion of Materials

Traditional Building Block Approach Improves Confidence by Extensive Testing Supported by Analysis:
Too Often Misses Material Insertion Windows



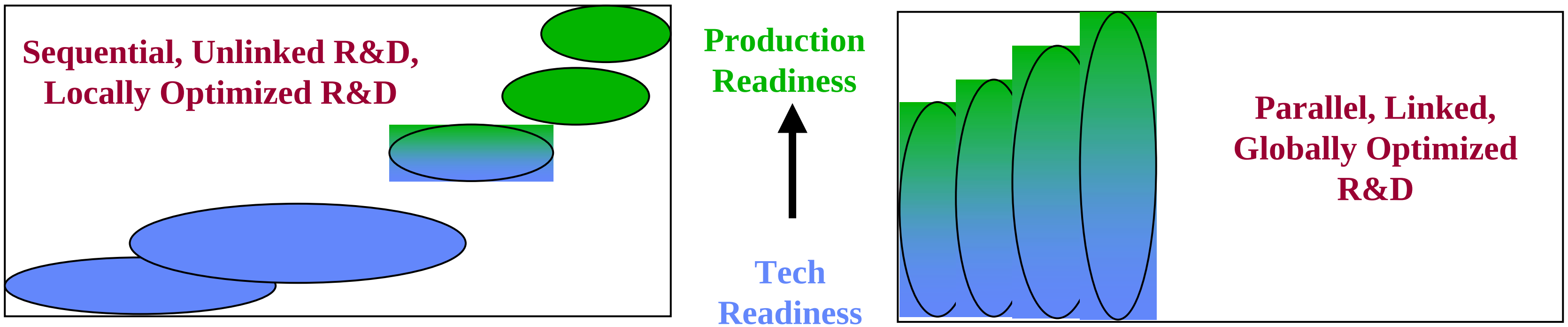
What AIM Enables

AIM Methodology Improves Confidence More Rapidly & Effectively by Analysis Supported By Test / Demonstration -
***Focusing* on the Designer Knowledge Base Needs**



Accelerated Insertion of Materials

Dr. Steven G. Wax, November 16, 1999
Gail Hahn, (314) 233-1848, gail.l.hahn@boeing.com



- **Development of Properties, Processing Done Without Quantifiable Link to Designer Needs**
  - **Processing Reality Requires Rework of Properties, Still No Link to Designer**
  - **Production Readiness Steps Reworks Technology Readiness**
    - » **Designer Knowledge Base NOT Ready Until Final Stages**

- **Development of Properties, Processing Explicitly (Through Models/Experiments) Linked to Designer**
  - **Development of Designer Knowledge Base Begins at Outset of R&D Based on Designer Needs**
  - **Time/Effort Refines Knowledge Base**
    - » **Driven by Properties, Performance, Accuracy Really Needed**

A New Paradigm in Materials Development is Required to Significantly Reduce the Timeframe of Insertion

DESIGN TEAM'S NEEDS

Requirements are Multi-Disciplined

Structural

- Strength and Stiffness
- Weight
- Service Environment
  - Temperature
  - Moisture
  - Acoustic
  - Chemical
- Fatigue and Corrosion Resistant
- Loads & Allowables
- Certification

Manufacturing

- Recurring Cost, Cycle Time, and Quality
- Use Common Mfg. Equipment and Tooling
- Process Control
- Inspectable
- Machinable
- Automatable
- Impact on Assembly

Supportability

- O&S Cost and Readiness
- Damage Tolerance
- Inspectable on Aircraft
- Repairable
- Maintainable
  - Accessibility
  - Depaint/Repaint
  - Reseal
  - Corrosion Removal
- Logistical Impact

Material & Processes

- Development Cost
- Feasible Processing Temperature and Pressure
- Process Limitations
- Safety/Environmental Impact
- Useful Product Forms
- Raw Material Cost
- Availability
- Consistency

Miscellaneous

- Observables
- EMI/Lightning Strike
- Supplier Base
- Applications History
- Certification Status
  - USN
  - USAF
  - ARMY
  - FAA

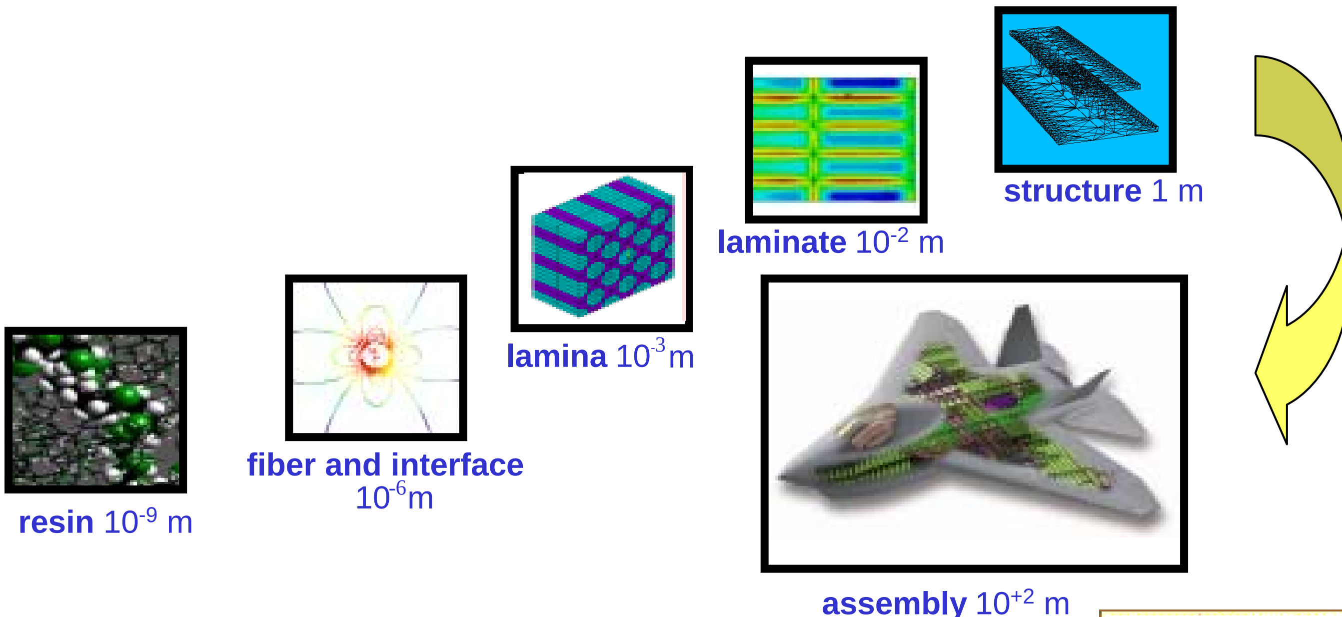
Risk in Each Area is Dependent Upon Application's Criticality and Material's Likelihood of Failure

Some Critical Issues

- **Knowledge Base Construction**
  - Content and Structure
  - Proper Mix of Experiments and Models
  - Knowledge of Uncertainty and Source
- **Linking of Scales**
  - Hierarchical Averaging Principles for Scaling (Without Losing Extremes)
- **New, Efficient Experimental Approaches (Including Legacy)**
  - Linked to Models
  - Compatible with Legacy Data
- **Propagation of Errors and Variations**
  - In Models and Experiments
- **Representation of Materials and Materials Properties**
  - Full Composition/Microstructure/ Defects
  - Model Independent, Measurement Independent
  - Amenable to Both Model and Experimental Determination

Home
Application
Certification
Assembly
Design
Supportability
Cost
Schedule
Strength
Fabrication
Quality
Mat'l & Proc
Legal/Rights
Output

Accelerated Insertion of Materials



Methodology
Process
New Features

Chemistry to Component in the Shortest Time at Acceptable Risk

DARPA TEAM

Edit Existing File | Compute Results | Save & Close

AIM-C BOEING

Boeing AIM - C Goals

AIM-Composites Will Take Us From Test Supported by Analysis to Analysis Supported by Test

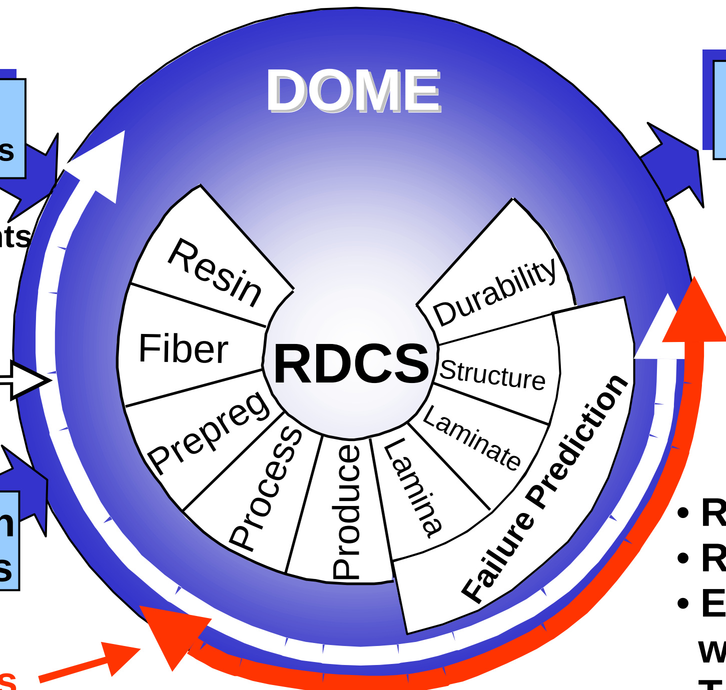
Designer Knowledge Base Driven

Designer Constraints = Designer Requirements

- Configuration
- Environmental Requirements
- Dimensional Tolerances
- Certification Requirements

Reduced Time

Application/Fabrication Concept Requirements



Reduced Costs

Designer Needs/Information

- Viable Design Options
- Element Level Properties for Structural Analysis
- Quality Capability
- Producibility Capability
- Variability Impact

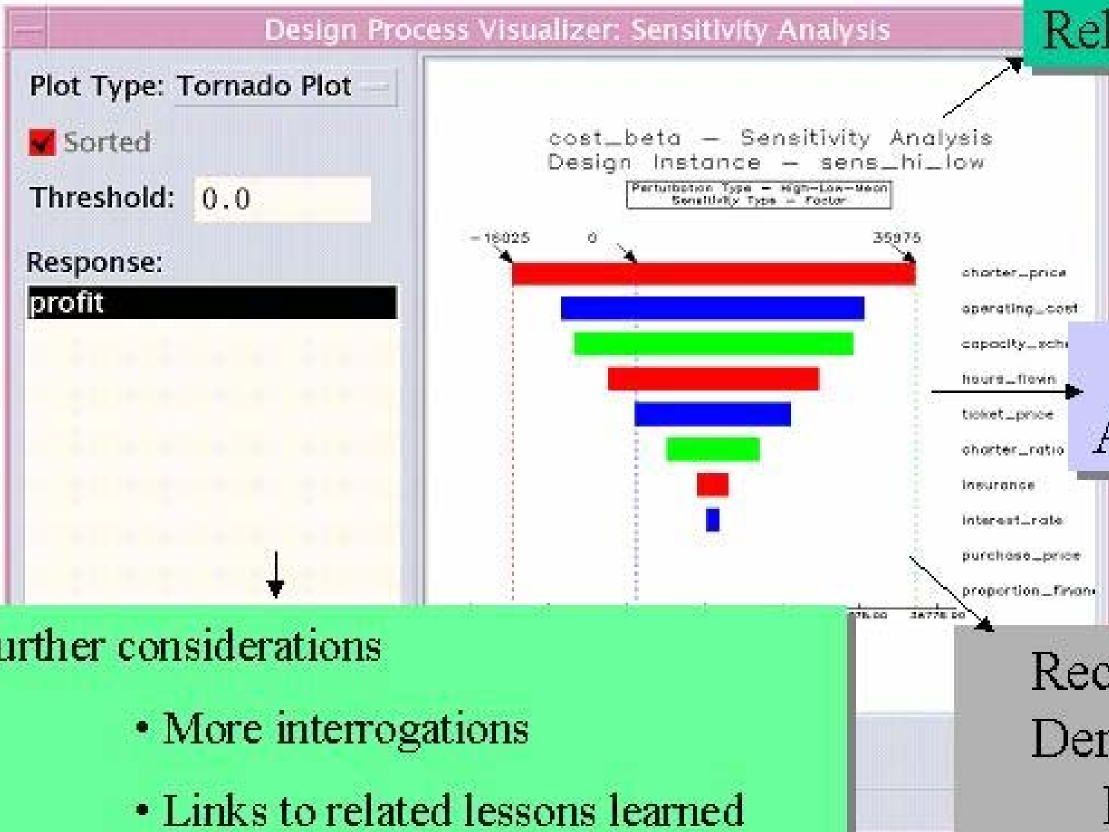
Payoffs

- Reduced Insertion Time
- Reduced Insertion Costs
- Expandable Methodology with Time and New Technologies

RDCS- Robust Design Computational Systems (Rocketdyne)
DOME- Distributed Object Oriented Modeling Environment (MIT)

Example Output of AIM-C Comprehensive Analysis Tool

Drivers of Cost, Schedule, Technical Outcomes



Related Tests

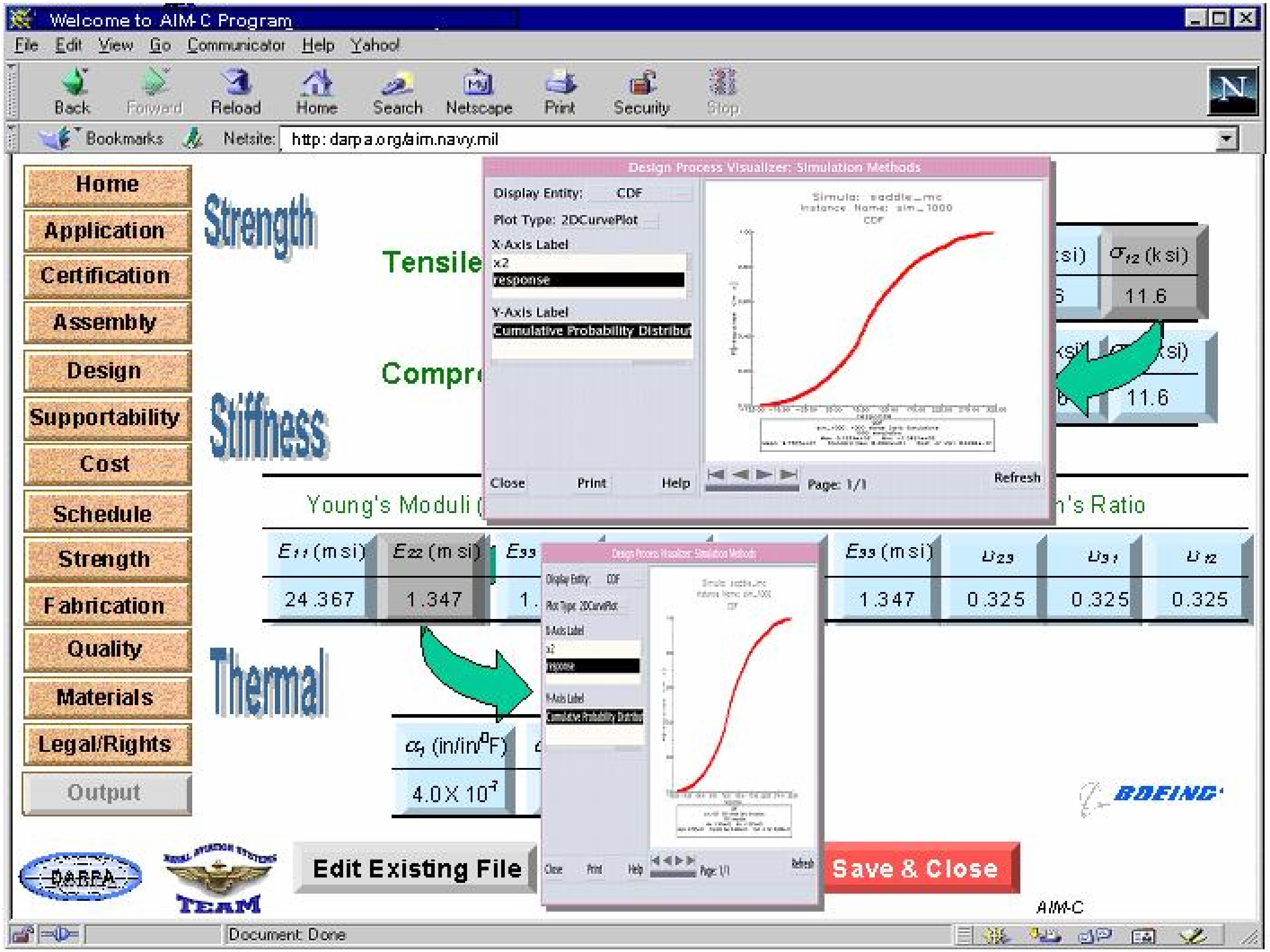
Recommended Analysis Methods

Recommended Demonstration Features

Further considerations

- More interrogations
- Links to related lessons learned
- Links to more information

Example Output of AIM-C Comprehensive Analysis Tool



AIM-C Comprehensive Analysis Tool Ties the Output to the Methodology

RDCS/DOME Framework

Structure Models (Science Based)

Material & Process Models (Science Based)

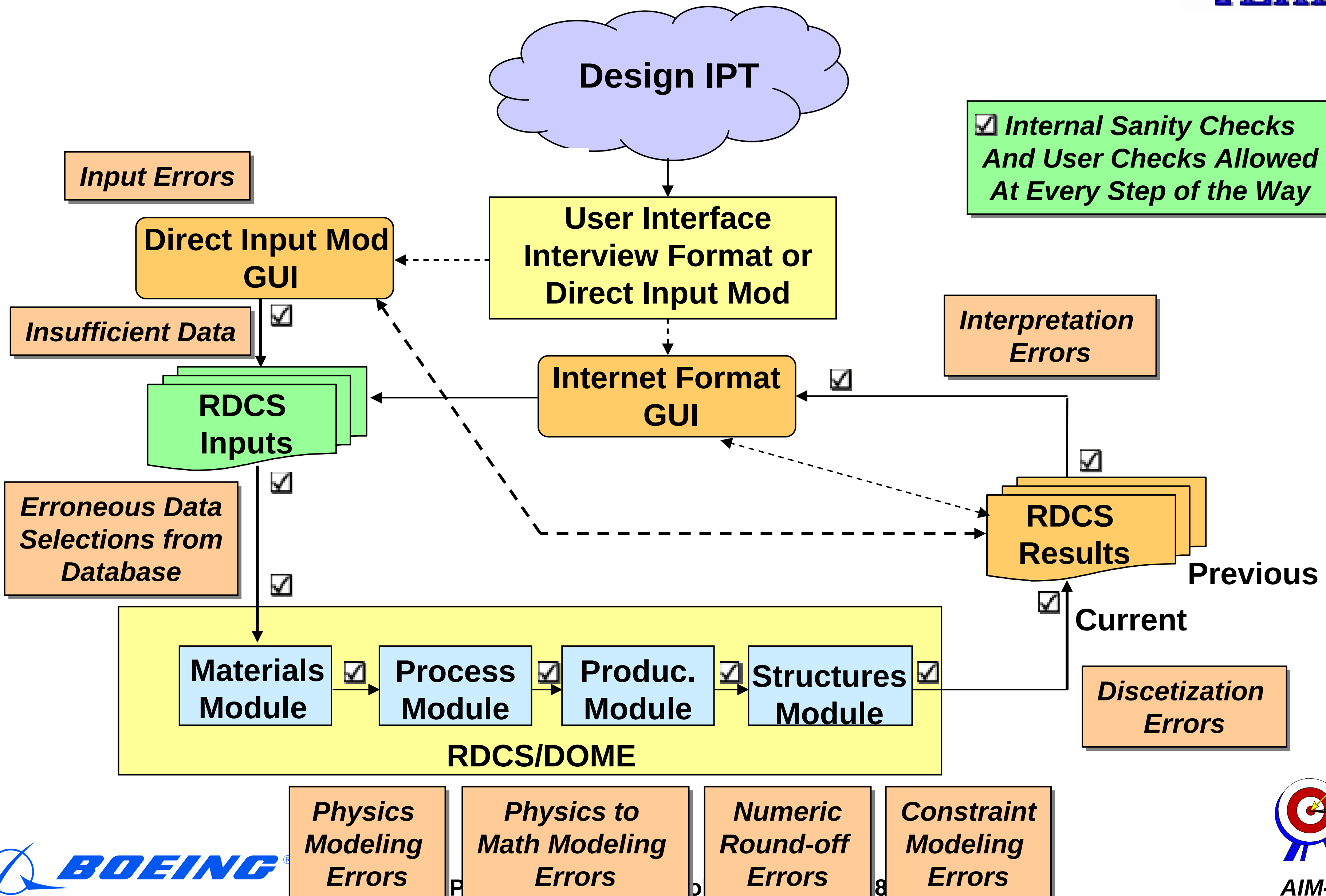
Producibility Models (Science Based)

Heuristic Models

Data Bases

Methodology

Error Sources and Mitigation in The AIM-C Product



AIM-C

AIM-C CAT Development Levels

Basic Product	Architecture Backbone in Place Limited Heuristic Link to Methodology Modules Very Limited Utility No AIM User Interface / Use existing DOME and RDCS interfaces
Optional Product	Architecture with Moderate Robustness Firm Heuristic Link to Methodology Modules with Validated Functionality Internet User Interface for Input
Phase II Product	Architecture Robust Firm Heuristic Link to Methodology Modules with Complete Functionality Internet User Interface for Real Time Input / Output Manipulation Capability

Industry Benefits from AIM

- Cost, schedule, performance with confidence factor
- Focus based on needs
- Knowledge management – orchestrated models, simulations, experiments to maximize useful information
- Built on building block methodology while facilitating discipline integration
- Internet access
- Path from criteria based to probabilistic based approaches
- Platform support for changes – bill of materials, pedigree, re-certification
- Design process application
- The best of emergent modeling and explicit modeling
- Applications to other problem sets

Improve productivity, facilitate radically new approaches to material insertion

"Building Block" Test Program

Kathryn L. Nesmith,
Roland Cochran and Denise Wong

May 21-24, 2001

Naval Air Systems Command
Air Vehicle Department
National Conference
Jacksonville, FL

Material/Process and Design Development

Material Selection
- Metals
- Composites

Manufacturing Process
- Process Development
- NDT Standards

Material Properties
- Repair
- Physical/ Chemical/ Processing
- Environmental Effects
- Mechanical Properties
- Statistical Knockdown
- Fatigue Scatter
- Effects of Defects

Elements/ Subcomponents
- Design Details
- Damage Tolerance
- Repair
- Validation of Analysis Methodology
- Fatigue
- Static
- Acoustic

Components
- Configuration Details
- Damage Tolerance
- Static
- Fatigue
- Repair
- Validation of Analysis Methodology

Reproduction Verification

Full Scale Laboratory

Certification Tests
- Static
- Fatigue
- Drop
- Dynamics

EMD Aircraft
- Flight Test
- Ground Test

Same Basic Building Block Process Used For Metals

Specifics for Polymer & Composite Material Certification

- Essential to look at materials and related process together
- "B"-Basis design allowables are used
  - Dependent on material form
- Experience from other programs can be used; however, ability to achieve properties must be demonstrated
  - Many test methods used are company proprietary

Polymer & Composite Material Properties

- Physical and Chemical
  - Tg
  - Density
  - Viscosity
  - Cure Kinetics
  - Out Time
  - Tack
- Environmental Effects
  - Fluid Resistance
  - Upper/Lower Use Temps
  - Thermal Cycling and Shock
  - Moisture Absorption
  - Vibration & Acoustic
- Mechanical Properties
  - Strength / Modulus
  - Notch Sensitivity
  - Fatigue
  - Adhesion
  - Damage Tolerance
  - All critical modes and environments

Products:
Material Specifications, B-Basis Design Allowables

Polymer & Composite Material Properties

- Effects of Defects
  - Mechanical effect of common defects
  - Voids, delamination, FOD, wrinkles, impact
- Repair
  - Develop repair materials and processes
  - Demonstrate utility

Product:
Engineering data to support part disposition
Repair specifications and procedures

Polymer & Composite Process Development

- Define process limits
  - Develop mechanical properties at limit
- Demonstrate reproducibility within the limits
- Define critical steps/tools/equipment
- Develop inspection and QC process

Product: Process specifications

Part Fabrication

- **Elements And Subcomponents**
  - Fabrication of design details
  - Validation of analysis
  - Further definition of inspection and repair requirements
  - Risk reduction for manufacturing and assembly
- **Components**
  - Fabricate actual components
    - Manufacturing demonstration
    - Destructive evaluation
  - Demonstrate repairs
  - Demonstrate component level mechanical performance
  - Validate analysis
  - Demonstrate systems interfaces
  - Demonstrate damage tolerance

Requalification of Polymer / Composite Parts

Graphite Composites

	Constituents	Equipment
• Fiber	Precursor Sizing	Precursor Fiber Lines Carbonization Fiber Lines
• Resin	Multiple Monomers & Polymers Solvents	Mixers
• Prepreg •Slit Tape	Impregnation Level	Prepreg Lines Slitter
• Fabric/Preforms		Weavers / Braiders

Requalification of Polymer / Composite Parts

- Part Fabrication Process Changes
  - New Process, Baseline Material
    - Example: Change to Selective Laser Sintering process of nylon reduced elongation by 90% compared to baseline process
  - Modification / Replacement / Relocation of Process Equipment
  - Change to Process Parameters Outside Qualified Process Window

Small Portion of ONR Protocol

Key

● - Must evaluate amount of testing requested to address this issue. No testing required may be an acceptable answer. Testing amount dependent upon contractual requirement, application, complexity and level of acceptable risk

Q – Typically required for quality control testing of each batch of material fabricated

☐ - - Test not required. Identified change is not anticipated to affect this property or a related property will identify this material as not being equivalent.

	New Fiber, New Resin, New Airframe	New Fiber, New Resin	New Resin, Baseline Fiber	New Fiber, Baseline Resin	New Process, Baseline Fiber & Resin	New Prepreg Supplier, Baseline F & R (mixes)	New Prepreg Supplier, Baseline F & R (buys)	New Fiber line, Baseline Fiber	New PAN line, Baseline Fiber	Mod to Qual. Fiber Line, Baseline Fiber
Fiber Characterization	●	●	Q	●	Q	Q	Q	●	●	●
Resin Characterization	●	●	●	Q	Q	●	Q	Q	Q	Q
Interface Characterization	●	●	Q	●	Q	Q	Q	●	●	●
Chemical	●	●	●	Q	●	●	Q	Q	Q	Q
Physical	●	●	●	●	●	●	●	●	●	●
Nominal Cure Process	●	●	●		●					
Nominal NDE Process	●	●	●							
Mechanical (Lamina)	●	●	●	●	●	●	●	●	●	●
Structural Properties (Static)										
Unnotched Tension	●	●	●	●	●	●	●	●	●	
Unnotched Compression	●	●	●	●	●	●	●	●	●	●
Pin Bearing	●	●	●	●	●	●	●			
Flexure (w/ & w/o holes)	●	●	●							
Others	●	●	●	●	●	●	●	●	●	●

Kathryn L. Nesmith,
Roland Cochran and Denise Wong

May 21-24, 2001

Naval Air Systems Command
Air Vehicle Department
National Conference
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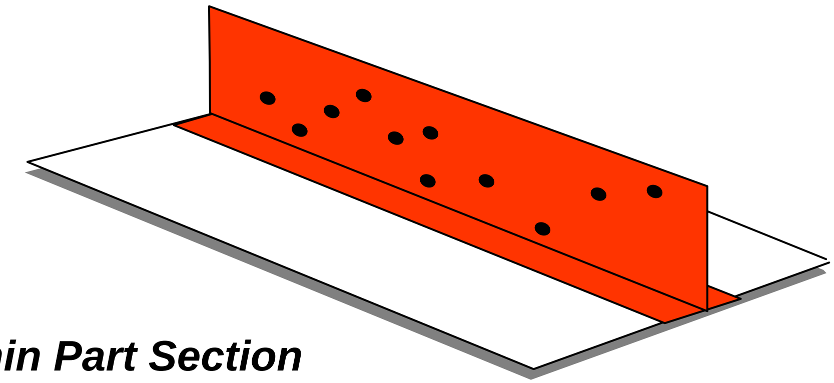
Summary

- Polymer & composite part certification differs in some ways from metallic structure
  - Very dependent on both material and processing from raw material to part fab
  - Allowables based on "B"-basis
  - 1st article destruct testing is needed for primary structure and significant secondary structure
- Requalification testing is required for changes in:
  - Raw material constituents (source, quality)
  - Equipment (new, modifications, relocation)
  - Processing parameters
  - Additional design certification may be required if material properties, component geometry or reaction to manufacturing processes are different than baseline component

Common Manufacturing Insertion Issues

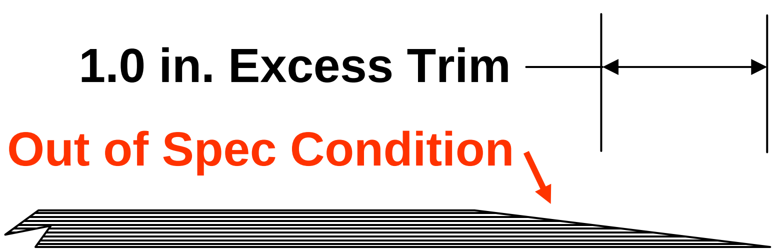


Thin Part Section
with Cocure Having Voids and Porosity

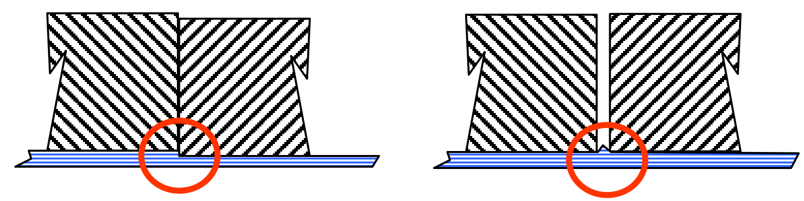
Process Specification Calls out ±6-7% Thickness Tolerance

Thickness Zoning

Thick Parts Having Large Thickness Variability (Within Parts and Part-to-Part)



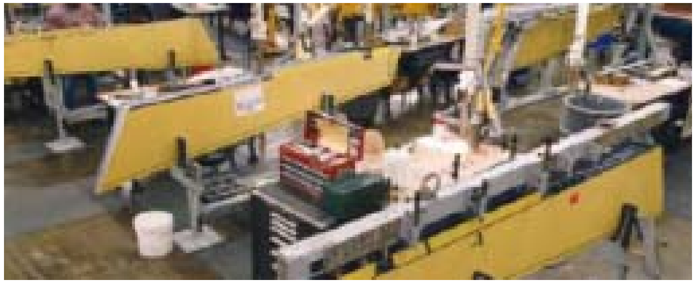
Edge Thickness Thinning for >1 in.



Complex Tooling Mismatches
Giving Steps and Puckers

Common Manufacturing Insertion Issues

Multiple Material Processing Compatibility (I.e. Structural Resin and Adhesives)



Microcracking in Large, Cocured Structure (Interactions of Different Material Cure Requirements and Tooling Concepts)

Process Specification/ Tooling Incompatibilities for Heat-up (Invar/Steel)

Insufficient Out Times (Never Enough)

Other Encountered Shop Issues

- Exotherm of Thick Parts
- Thick/Rigid Part Distortion
- Incorrectly Compensated Spring-in Angles
- Prepreg Tack
- Secondary Processing Requirements (Drying, Peel Ply, Sanding, Bonding, Painting, etc.)

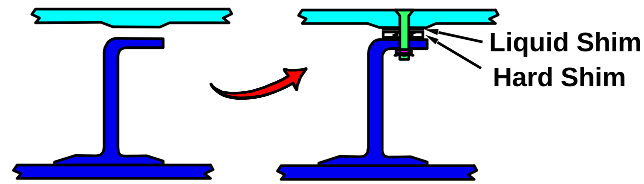
Other Encountered Issues

- Resin Solvent Resistance
- Microcracking with Cure, Thermal Cycles, and/or Moisture
- Moisture/Solvent Absorption with Plastization and/or Reduced Tg
- Incompatibility of Resin Characteristics and the Manufacturing Process
- Final Part Accuracy/Repeatability Relative to Tooling Concepts

Precision Assembly for Composite Structures

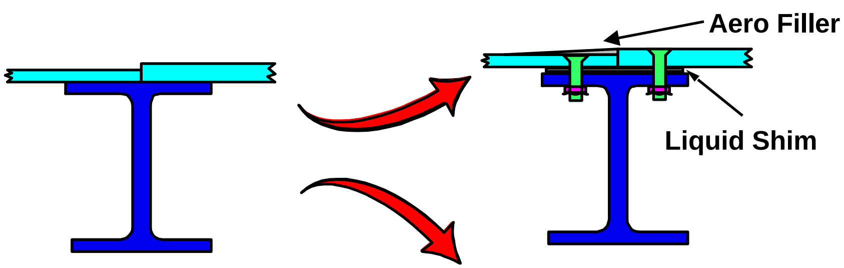
Background

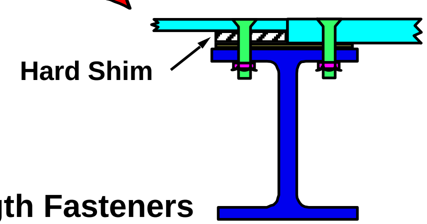
Assembly Variations



- Hard Shim Required for Gaps in Excess of .03 in.
- Engineering Disposition
- Multiple Grip Length Fasteners

Surface Fidelity Variations





- **Rework**
  - Shimming
  - Moldline Splining
- **Multiple Grip Length Fasteners**

Major Variation Types

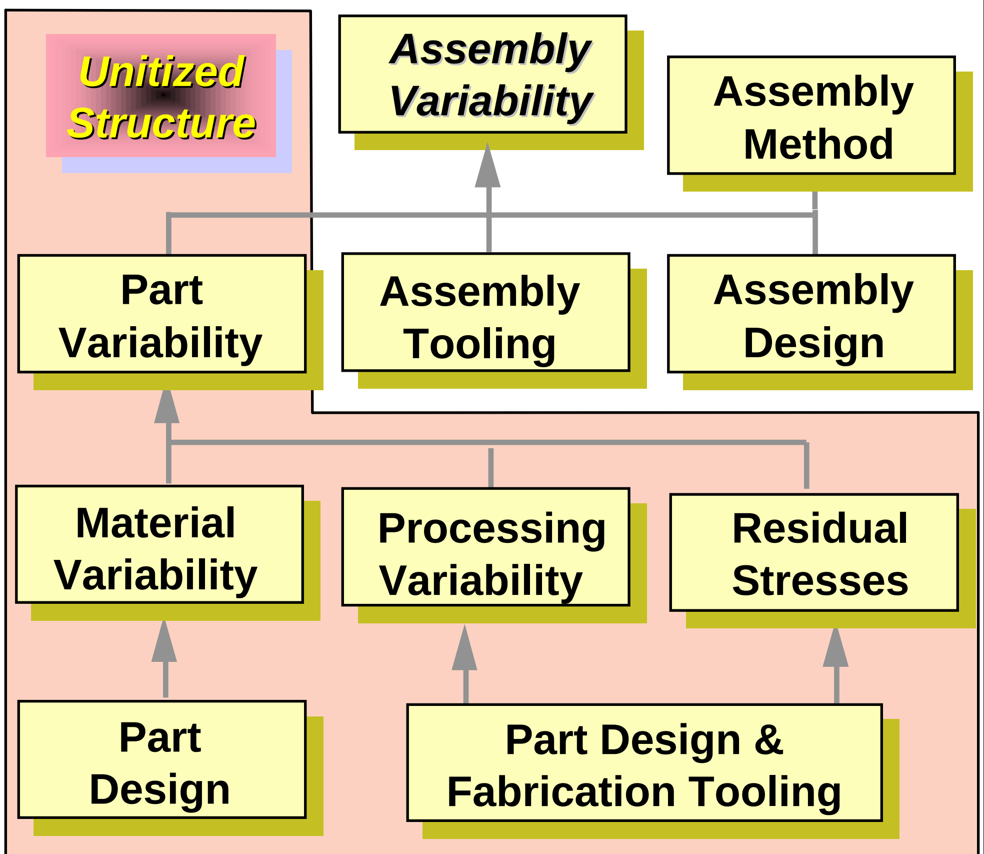
Part Mismatch
- **Skin-to-Substructure**
- **Substructure-to-Substructures**

Moldline Fidelity
- **Skin-to-Door**
- **Skin-to-Access Panel**
- **Skin-to-Skin**

Precision Assembly for Composite Structures

Subtask 1 - Root Cause Analysis

Variability Flow Chart

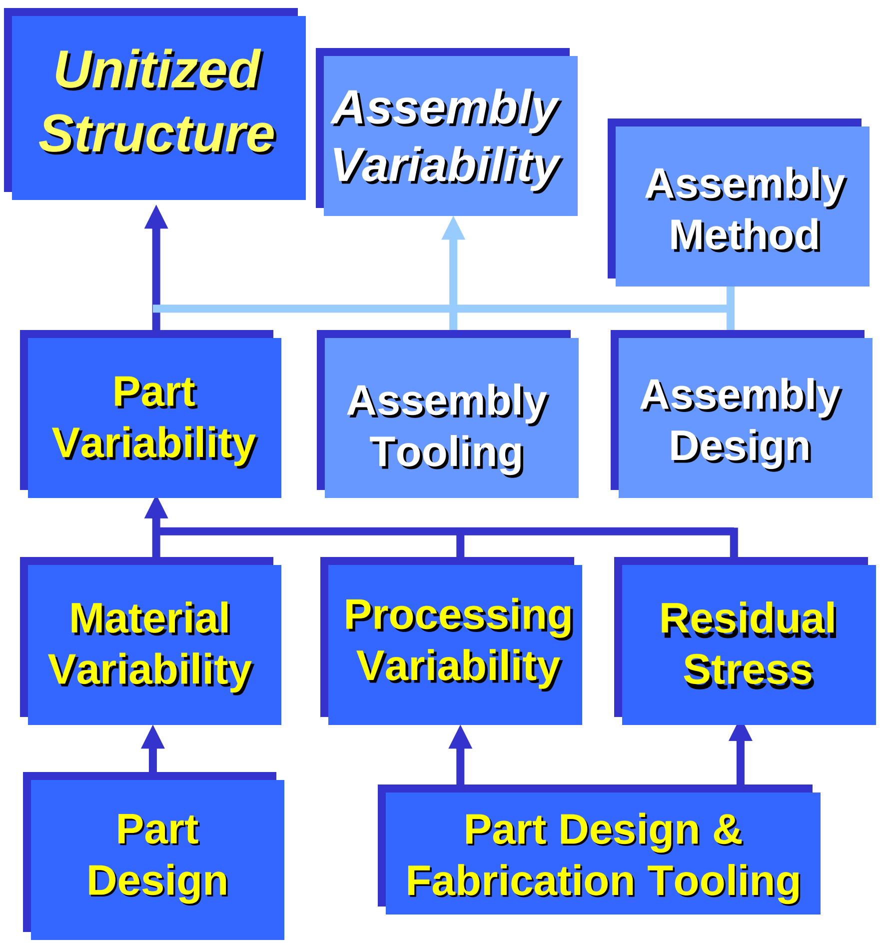


Level	Factor	Item/Cause
Assembly	Assembly Design	Concepts (Piece Parts, Subassembly/Assembly), Length, Width, Thickness
	Part Variability	Materials, Processing, Fabrication Design, Fabrication Tooling, Warpage
	Assembly Tooling	Primary Tool, Details, Accuracy, Repeatability, Tool/Part Coordination
	Assembly Method	Assembly Sequence, Fastener Types, Hole Drilling/Countersinking, Fastener Installation Method
Fabrication	Material Variability	Prepreg, Reinforcement, Resin
	Processing Variability	Cure Pressure, Bagging, Debulking, Out Time, Resin Content
	Residual Stress	Materials, Processing, Tooling, Designs
	Part Design	Length, Width, Thickness, Configuration, Ply Orientations
	Fabrication Tooling	Primary Tool, Caul Sheet, Accuracy, Repeatability, Tool/Part Coordination

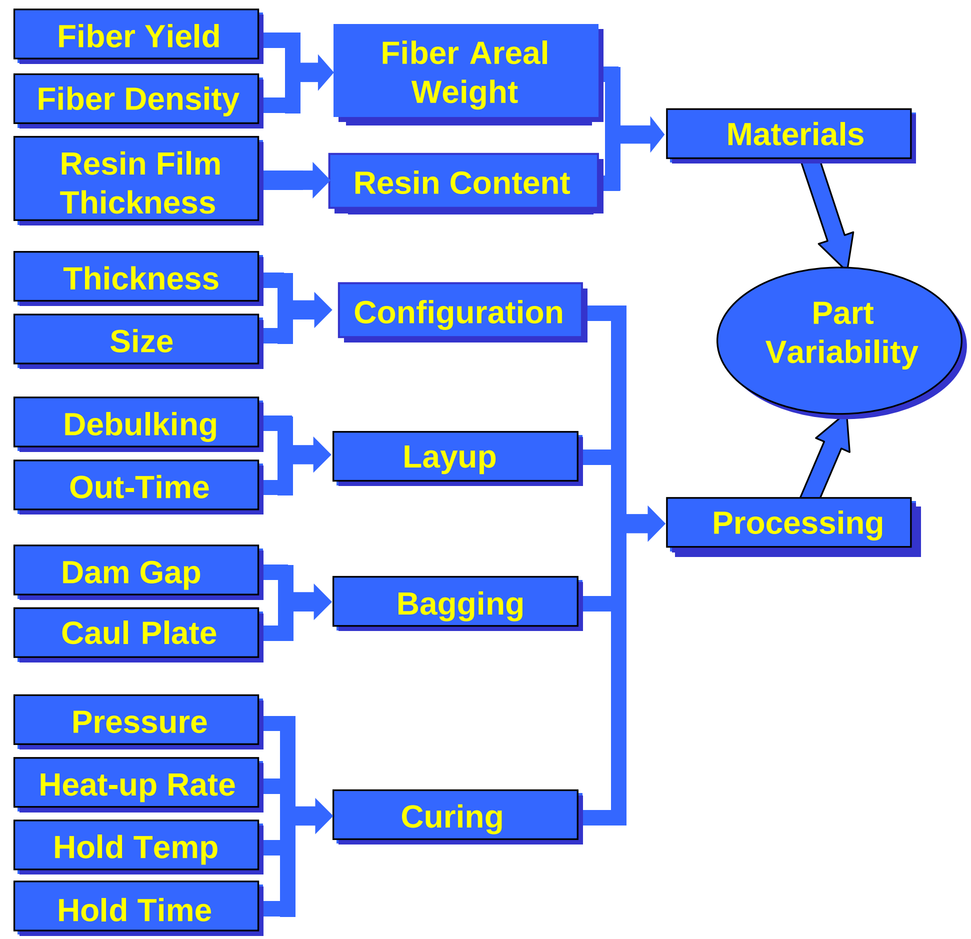
Precision Assembly of Composite Structures

Assembly Variability

Variability Flow Chart



Material and Processing Part Tolerance Accumulations

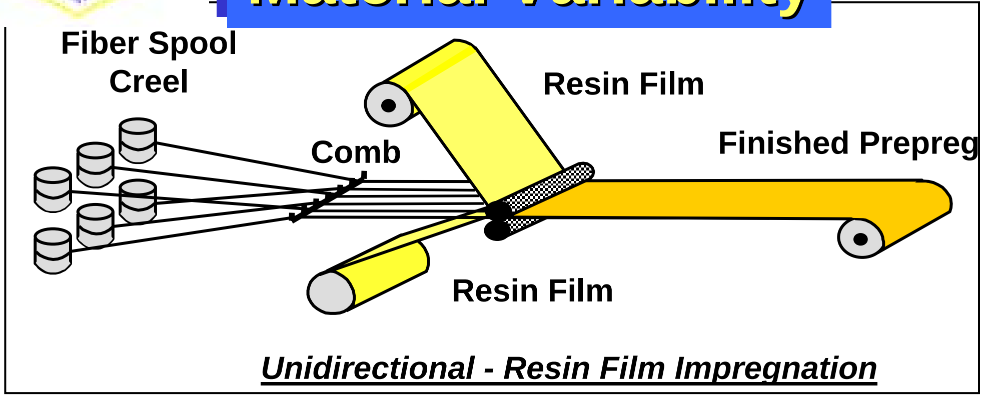


Part Variability Factors

Design	Materials	Processing	Cure	Tooling
• Orientation • Thickness • Size	• Unidirectional • Cloth • Net Resin • Excess Resin • FAW • Resin Content • Prepreg Manufacturing	• Material Out Time • Bleeder • Inner Bag Perforations • Dam Gaps • Dam Type • Debulking	• Pressure • Vacuum • Heating Rate • Hold Temp • Hold Times	• Caul Plate

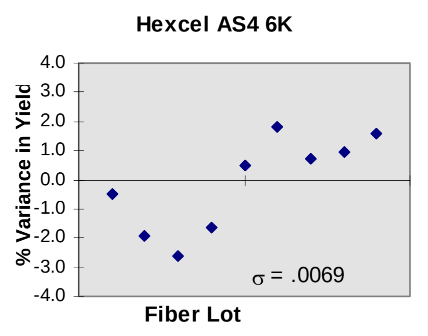
Precision Assembly of Composite Structures

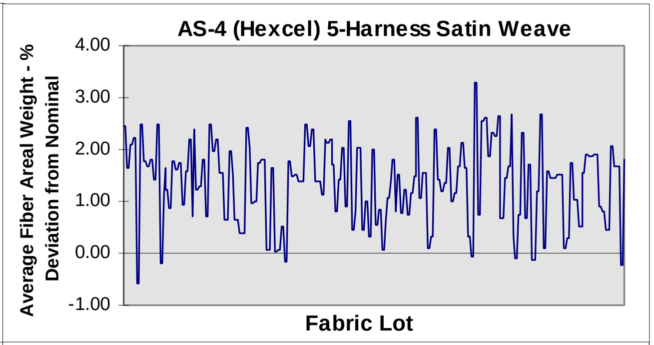
Material Variability

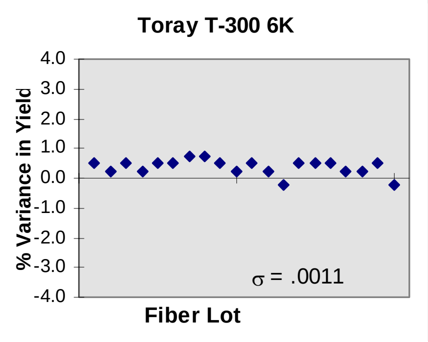


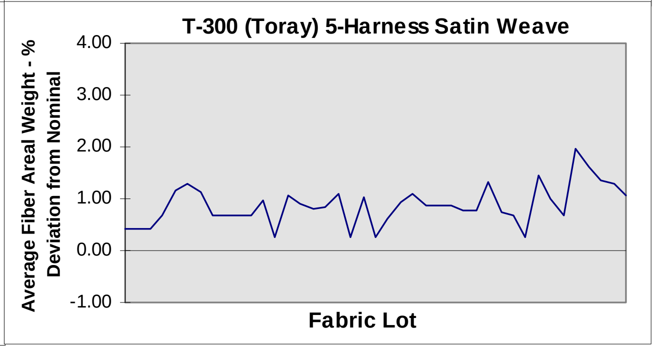
Unidirectional - Resin Film Impregnation

Fiber Variability (210 Batches)

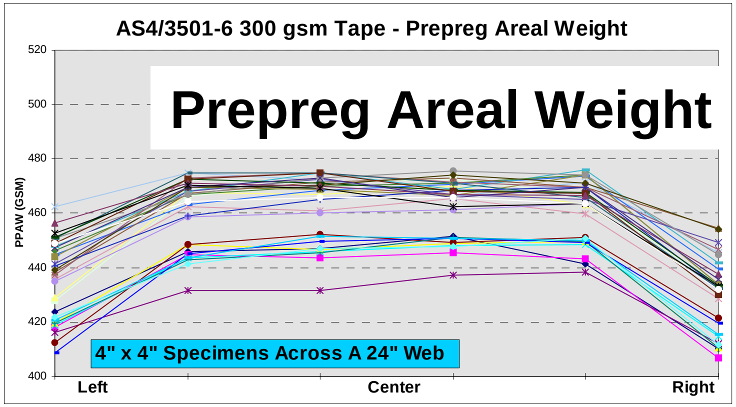


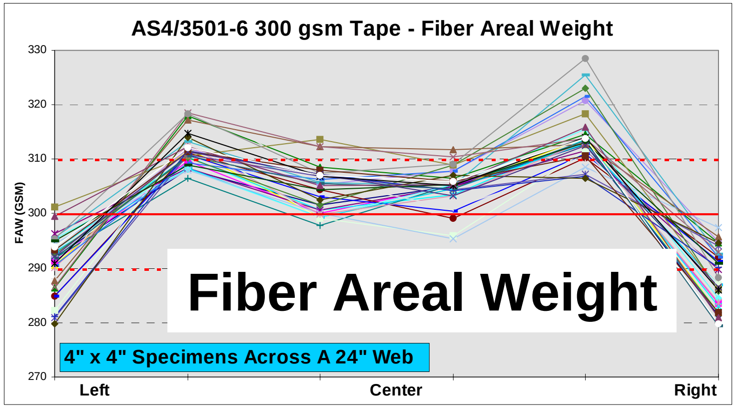






Prepreg Variability (21 Batches)



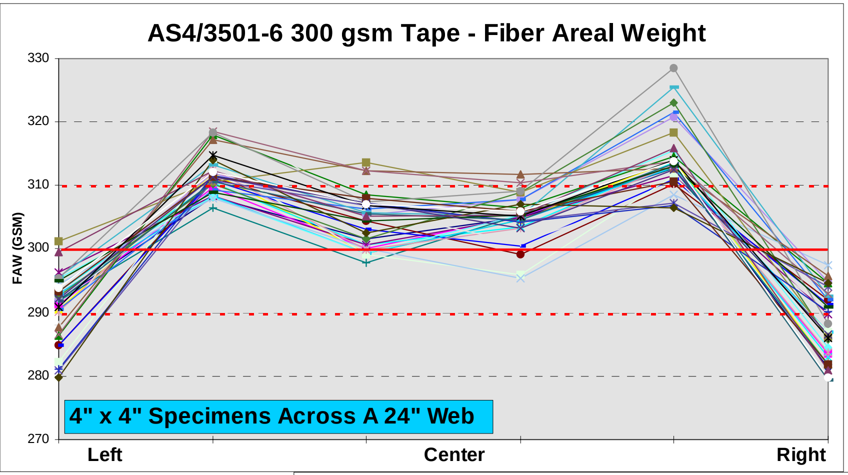


- Fiber Yield Variation Translates to Fiber Areal Weight Variation (Cloth)
- Prepreg Variation is Driven By Fiber Areal Weight Variation

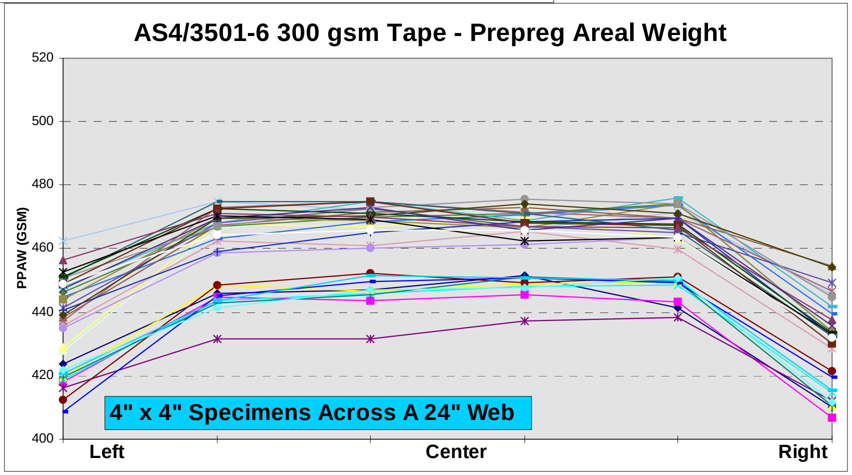
Precision Assembly for Composite Structures

Subtask 1 - Material Variations
Material Variability Assessment

...Prepreg Areal Weight Versus Fiber Areal Weight



- 4”x4” Specimens Taken Across A 24” Web
- 46 Rolls of Material Tested - 36 Excess Resin, 10 Net Resin

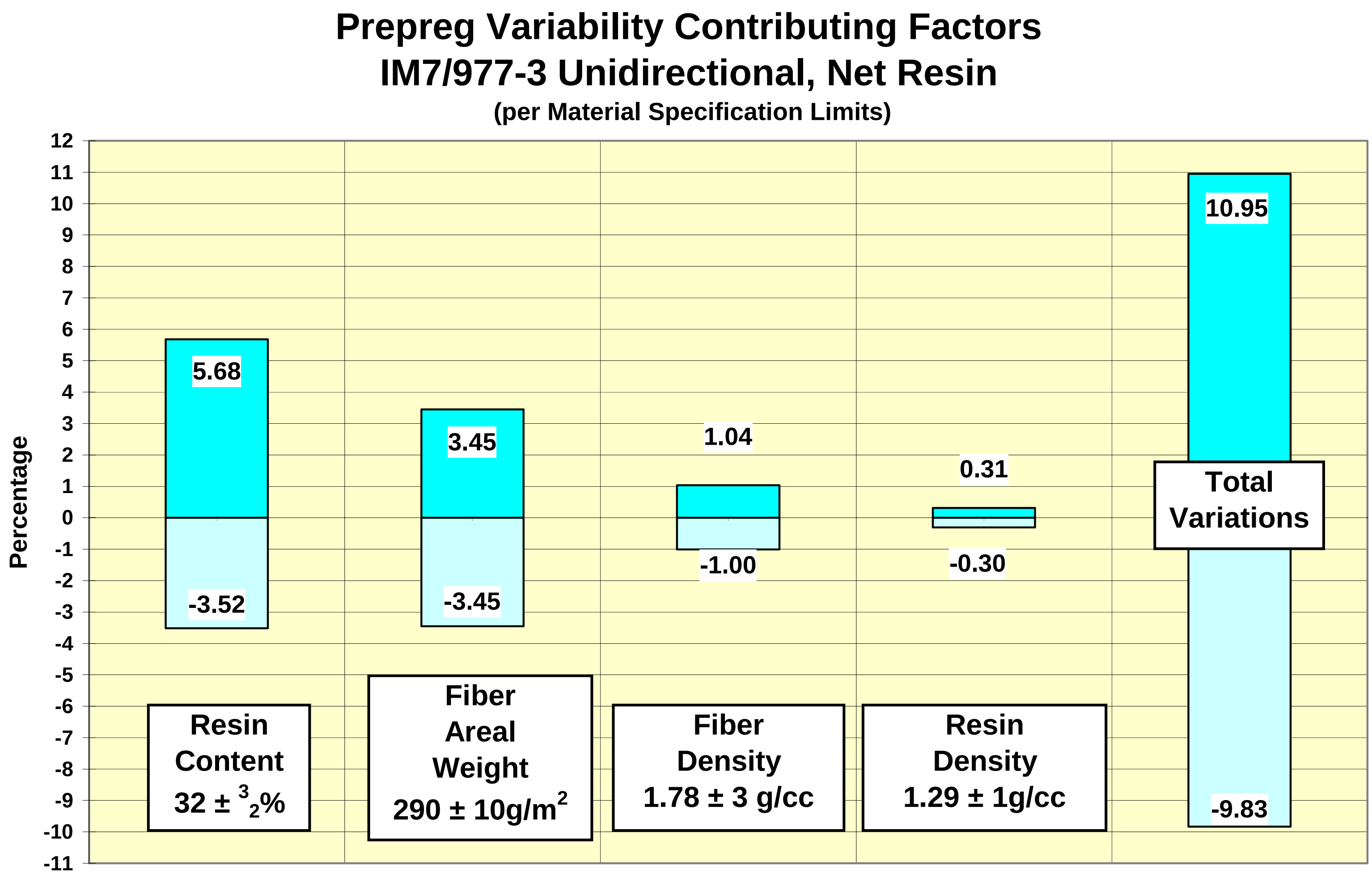


Significant Edge Effect on Prepreg Areal Weight Due Mainly to Edge Drop-Off Of Fiber Areal Weight

Precision Assembly of Composite Structures

Material Variability

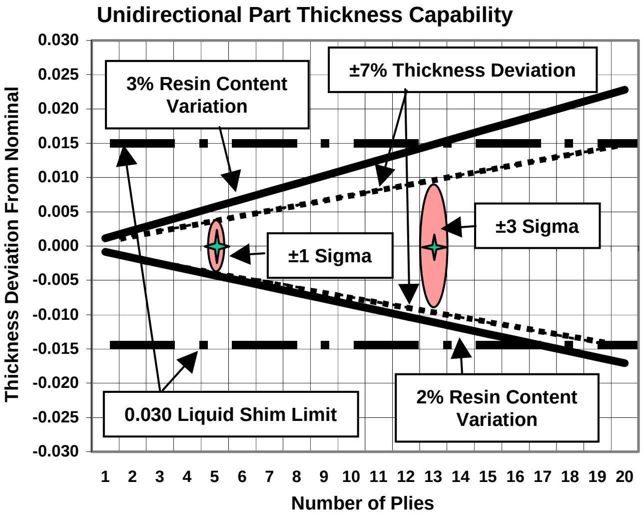
Theoretical Prepreg Variability

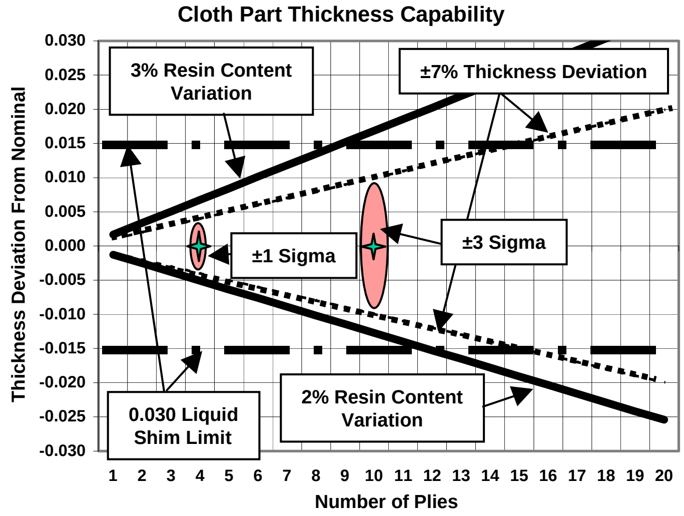


Precision Assembly of Composite Structures

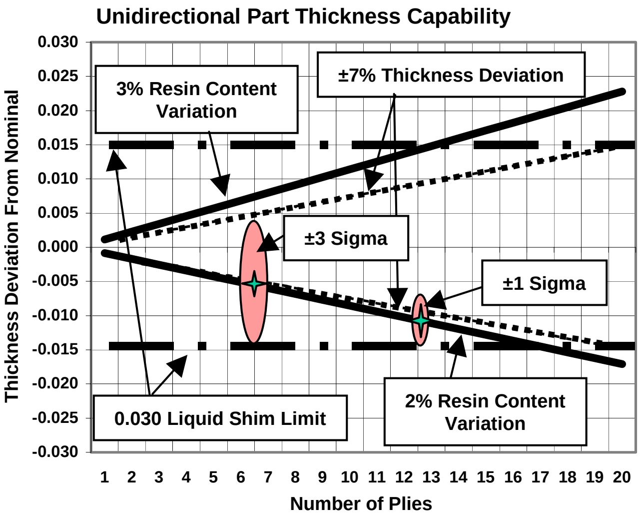
DARPA

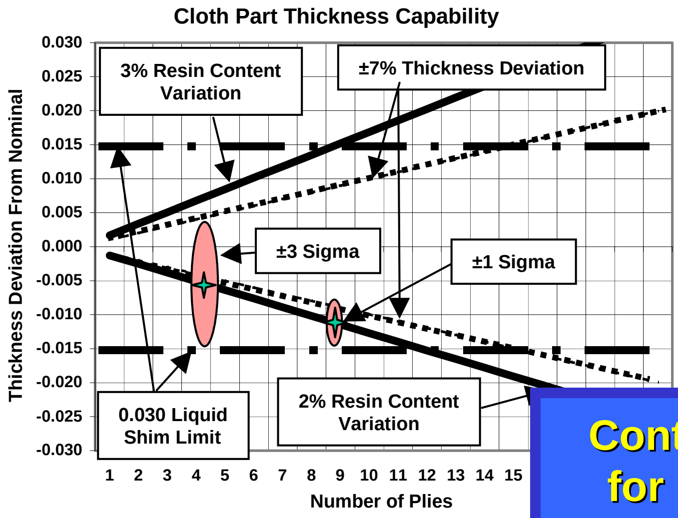
Material Variability - Process Capability





±1 and ±3 Sigma Process Capability for Thickness





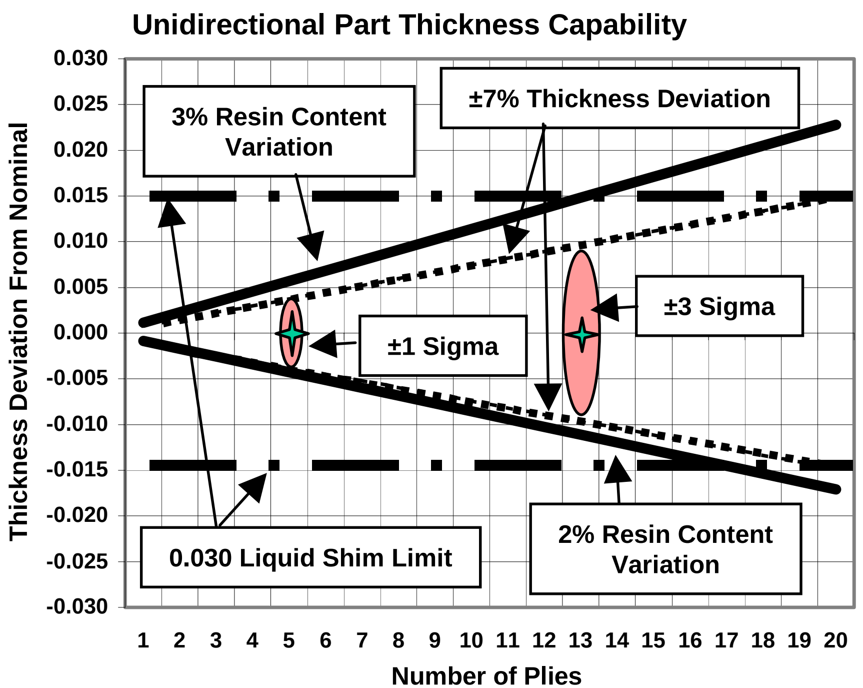
±0.015 in. for Liquid Shim Maximum Tolerances

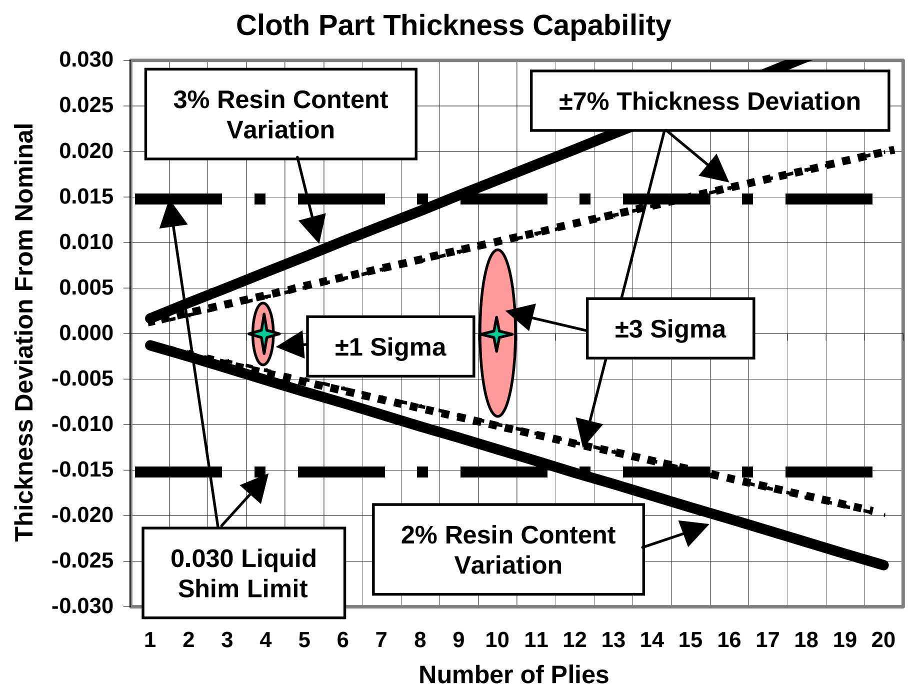
Contradictory Requirements for Process Capability and Assembly Tolerances

Precision Assembly of Composite Structures

Material Variability - Process Capability

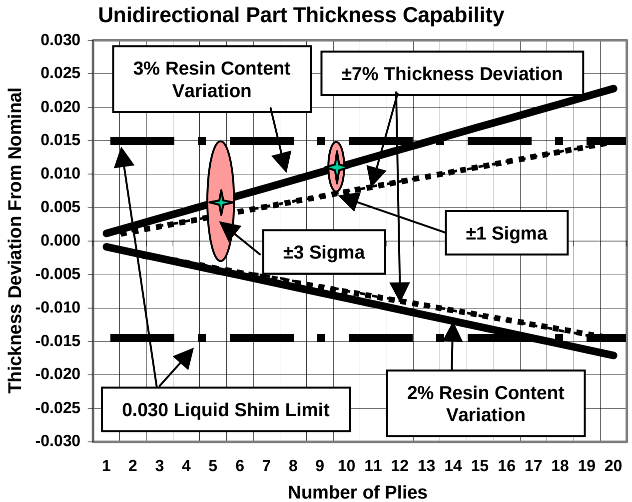
±1 and ±3 Sigma Process Capability for Thickness

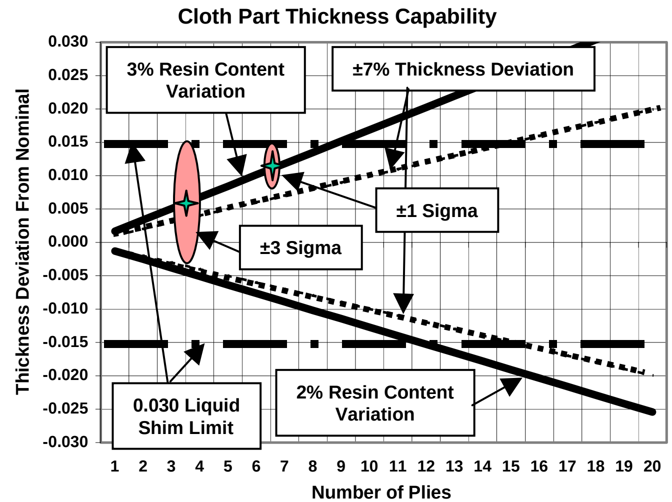


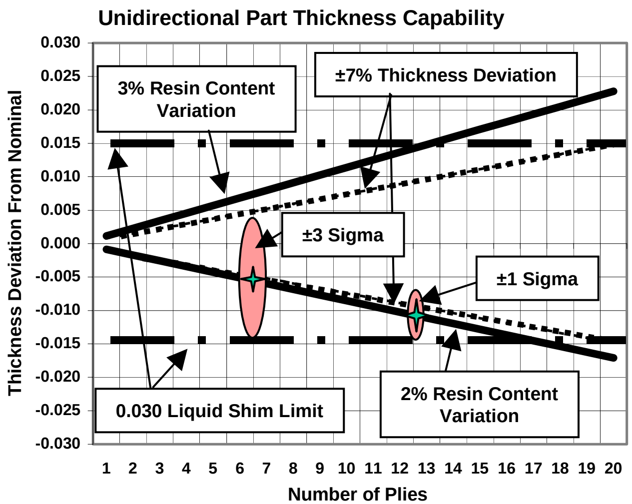


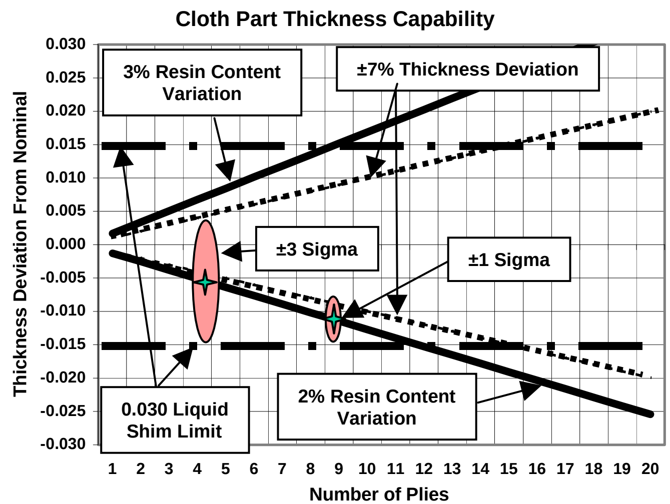
…………………The Probability of Consistently Achieving ±7% Desired Part Thickness is Very Low!

Material Variability - Process Capability









- With Existing Tolerances on Prepreg Materials, It is Difficult to Maintain ±0.015 Inch Liquid Shim Assembly Requirements

…………………Process Spec and Assembly Requirements are Mutually Exclusive With ±3 Sigma Process Capability !

Primary Model Usage Times

Conceptual Design

- Material Options
- Processing Options
- Part Configurations
- Tooling Options

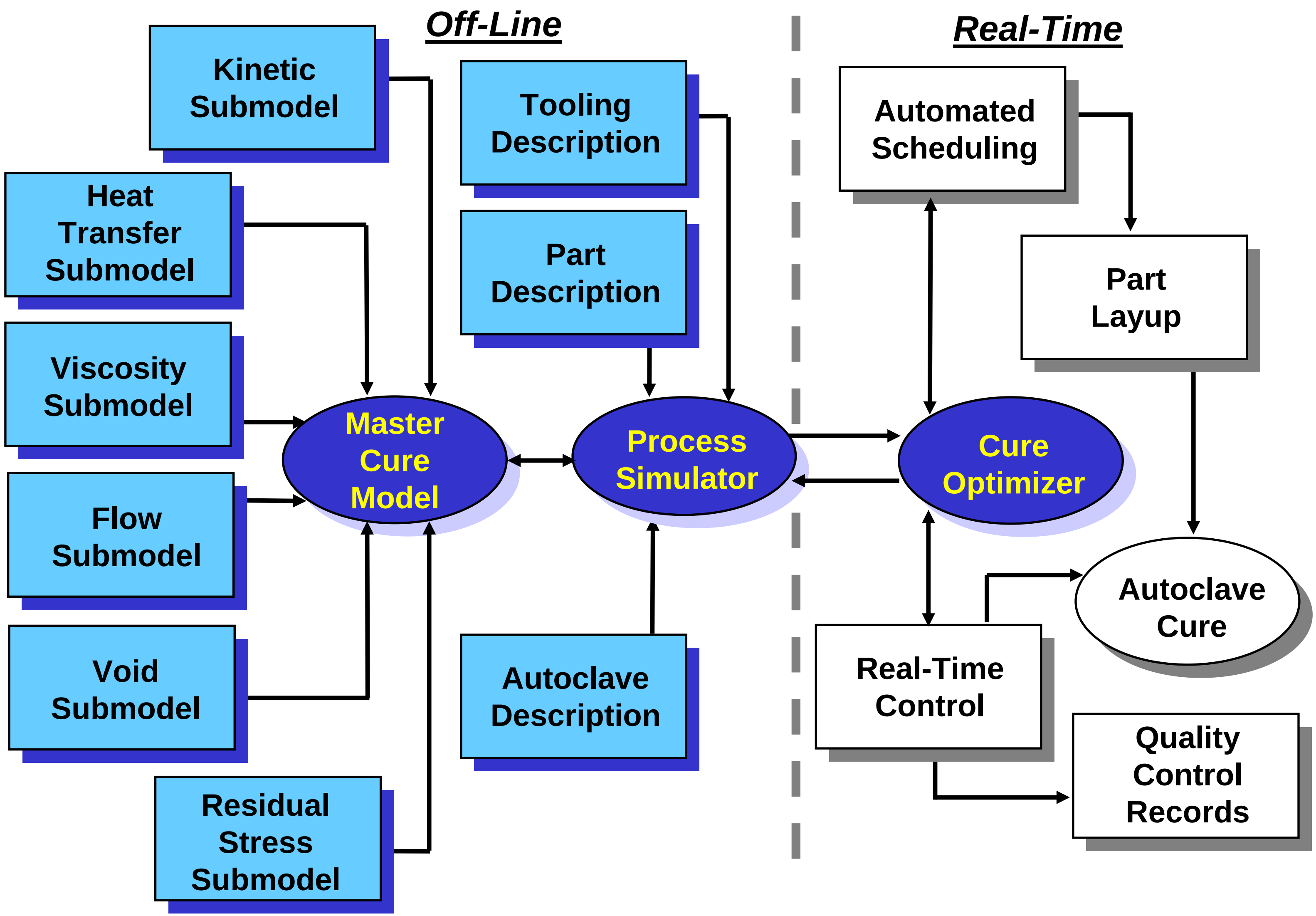
Detailed Design

- Material Specs
- Processing Specs
- Part Configurations
- Tooling Options

Part Fabrication

- On-Line Control
- Quality Dispositions

CACC Cure Process Modeling



DARPA

NAVAL AVIATION SYSTEMS TEAM

Understanding and managing uncertainty is an integral part of the AIM Materials and Processes approach

- Present clear traceability to data input pedigree
- Identify when models are out of their predictive bounds, validated bounds
- Collect uncertainty information as calculation progresses

Practical Aspects of Managing Uncertainty

- Indirect property measurement often required
- Testing expense and/or history can limit data populations
- Assumptions necessary to develop efficient models
- Focus on significant inputs (can vary from case to case)

- Input Material Properties
  - Test methods – accuracy, repeatability
  - Distribution – data correlation, population

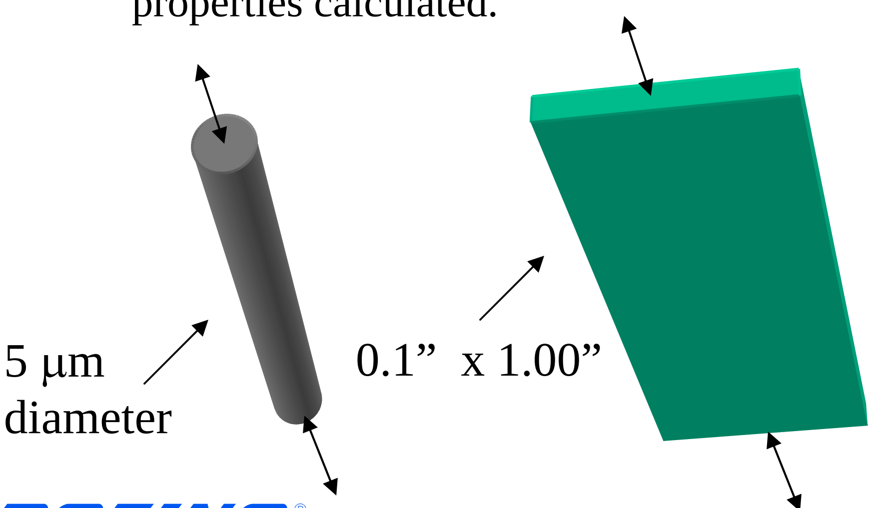
- Modeling
  - Accuracy of physics
  - Assumptions
  - Interpolation, extrapolation of input datasets

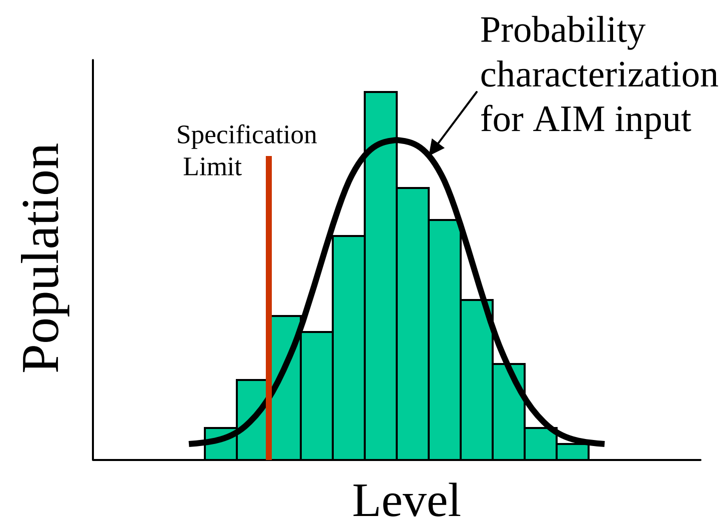
- Output values
  - Interpolation, extrapolation of output datasets
  - Post processing of data

•Input Material Properties

- Test methods – accuracy, repeatability
- Distribution – data correlation, population

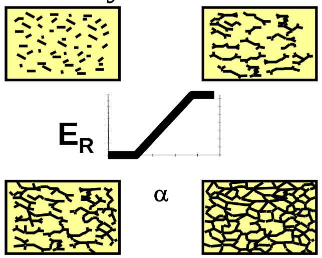
Example:
Fiber properties
single fiber tests not practical
Laminate tests performed, fiber properties calculated.





Example:
Actual data may not be ideal distribution shape, Distribution of material actually used may be truncated by specification acceptance criteria

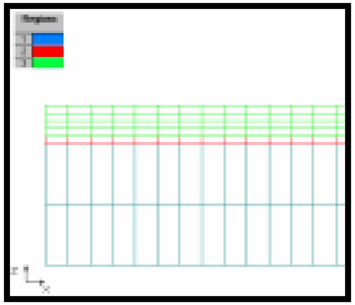
Example: Unknown mistake in calibrating DSC leads to wrong heat of reaction and incorrect temperature history



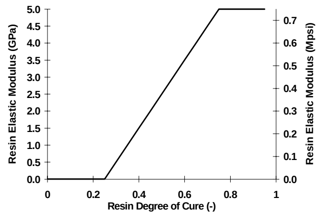
•Modeling

- •Accuracy of physics
- • Use of models outside of known limits
- • Code Bug

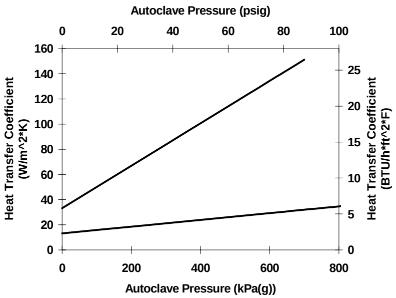
Example: The tool surface finish is not uniform for a tool or between tools.



Example: Physics of cure-hardening linear elastic versus fully viscoelastic



Example: Autoclave heat transfer equation is used outside of known limits



Modeling of the Resin

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Degree of Cure	batch to batch variation in rate of reaction.	Validity of the form of the equation; including physical basis: empirical, semi-empirical …	Use of model outside of bounds (eg temperature range, rates). In general modules should be self-checking. Are all input parameters within predefined bounds?	DSC not calibrated; base-line choice (Need to track history of usage – at all levels. Over time this will reduce uncertainty due to this)
Modulus	Specimen to specimen variation; batch to batch variation.	For partially cured materials, the assumption of cure hardening, linear elastic response. For cured materials, the response under mixed mode loading.	Use of model outside of bounds (eg strain range). Approximation of straight line fit to curve.	Testing machine not calibrated. Poor specimen preparation; poor strain measurement techniques.
Strength (to failure)	Specimen to specimen variation; batch to batch variation.	Definition of failure; particularly for some loading cases. Initiation versus propagation of a crack.	Use of model outside of bounds (eg temperature range).	Testing machine not calibrated. Poor specimen finish, poor alignment in grips.
Strain (to failure – linked to strength)	Specimen to specimen variation; batch to batch variation. This value is correlated with strength and somewhat to modulus	Definition of failure; particularly for some loading cases. Initiation versus propagation of a crack.	Use of model outside of bounds (eg temperature range).	Testing machine not calibrated. Poor specimen finish, poor alignment in grips.

Modeling of the Prepreg

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Prepreg Degree of Cure	Carried forward from resin module	Assumption that the fiber does not affect the resin reaction behavior.		Coding errors (bugs)
Prepreg Volume Fraction of Fiber	Point to point variation along width and along length of prepreg. Effect of combination of many layers to form the structure thickness.	Assumption that there are no visible voids	Use of a pre-defined value for compaction of layers due to pressure application	Poor measurements in acid digestion tests, optical techniques, etc.,.
Aerial weight	Correlated value with prepreg volume fraction of fiber, ply thickness, and resin and fiber densities			
Prepreg ply thickness	Correlated value with aerial weight and volume fraction of fiber			Difficulty in measurement of a small value that varies across the width and along length

Modeling of the Process

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Temperature Boundary Conditions	Variation in temperature throughout an autoclave; variation in bagging thickness across part	Modeling of heat transfer coefficient of autoclave includes pressure effect but not shielding of part. Assumptions made about tool-part resistance.	Convergence of mesh must be checked. Time-steps and temperature steps must be small enough.	Errors in setup files, and other initialization procedures. Errors/bugs in code.
Tool Part Interaction	Part to part and point to point variations in tool finish and application of release agent	Tool-part interaction is very complex, and very local effects may at times be significant	Current model of tool-part interaction is too simple for large parts on high CTE tools.	Errors in calibrating the tool-part interaction
Layup	Variation in lay-up during hand or machine lay-up.	The layers are smeared within an element and it is assumed that the smeared response is representative		Error in defining layup, or alternatively errors in the manufactured part compared to model
Residual Stresses	Many parameters can affect residual stress: local fiber volume fraction, …	Micro-stresses are considered to be independent of meso-stresses; there are few independent measurements of residual stress.	The formulation is believed to be most accurate when the cure cycle temperature is higher than the Tg. Otherwise the residual stress calculated can be an overestimate.	Errors in material property definition, errors in coding, errors in integrating process and structural models.

Modeling of the Fiber

<table>
<tr>
<th></th>
<th>Inherent variations associated with physical system or the environment (Aleatory uncertainty)
Also known as variability, stochastic uncertainty
E.G. manufacturing variations, loading environments</th>
<th>Uncertainty due to lack of knowledge (Epistemic uncertainty)
inadequate physics models information from expert opinions.</th>
<th>Known Errors (acknowledged)
e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm</th>
<th>Mistakes (unacknowledged errors)
human errors e.g error in input/output, blunder in manufacturing</th>
</tr>
<tr>
<td>Coefficient of thermal expansion, $\alpha 1$, $\alpha 2$</td>
<td rowspan="4">Batch to batch variation in material, arising from variations in PAN precursor, and carbonization process</td>
<td rowspan="4">Models almost always assume no temperature or moisture effect.</td>
<td rowspan="4">Lack of direct measurement techniques; property is measured on a lamina/laminate basis.</td>
<td rowspan="4">Back-calculation values based on micromechanics. Complex experimental methods.</td>
</tr>
<tr>
<td>Modulus (E11, E22)</td>
</tr>
<tr>
<td>Strength (to failure)</td>
</tr>
<tr>
<td>Strain (to failure – linked to strength)</td>
</tr>
</table>

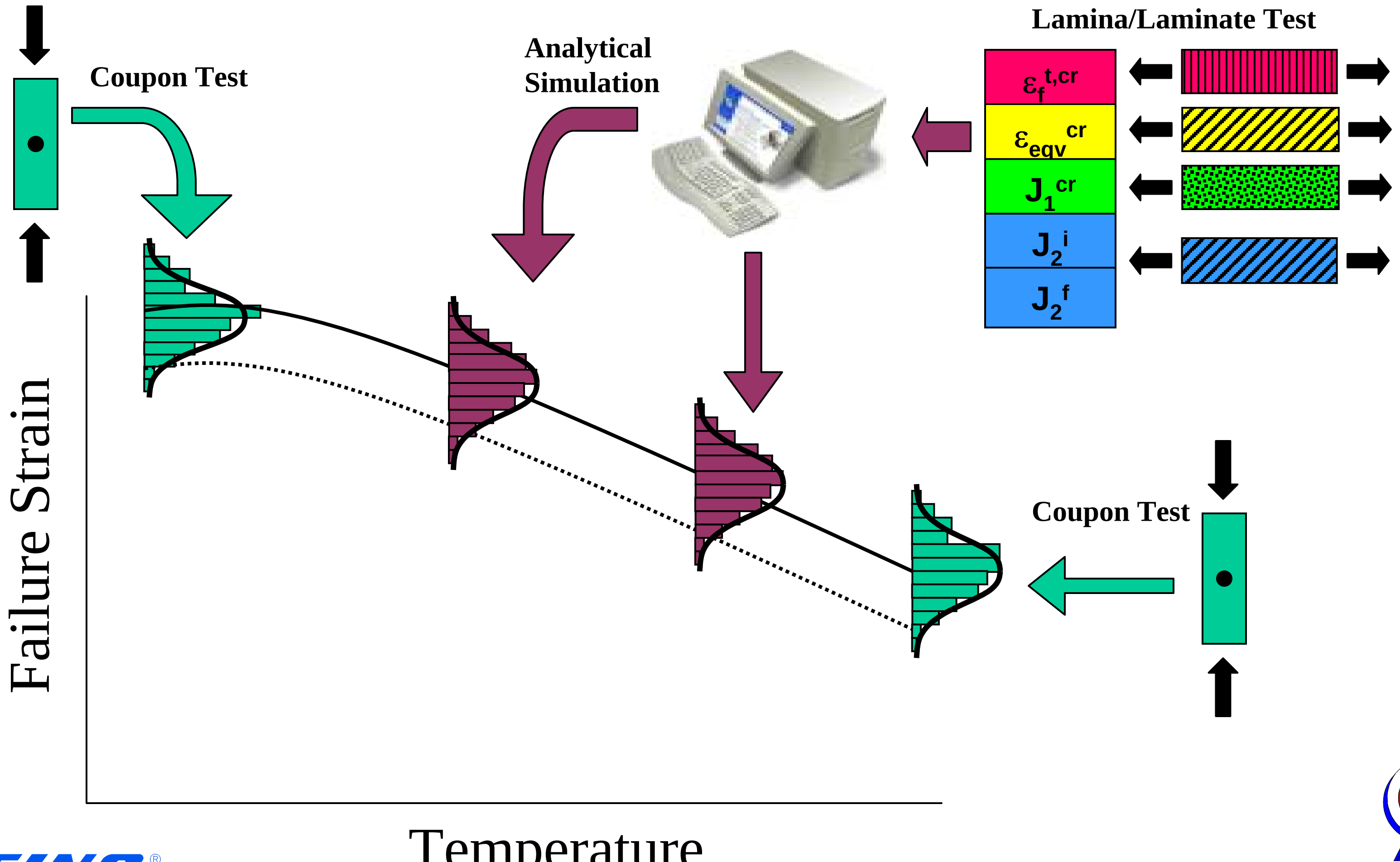
Stochastic Variables

Fiber Module

Modulus E1	(Fi_E1_analog)
Strength S1	(Fi_strth_1_analog)
Strain St1	(Fi_strn_1_analog
Thermal Expansion Alpha	(Fi_rho_analog)
Yield Yd	(Fi_tw_yld_analog)

Short Term Issues

- Prediction of Coupon Stiffness, Damage Initiation, and Failure Loads
  - Typical Properties
  - B-Basis Allowables
- Obtaining Design Values from Mixed Test and Analysis Data



Long Term Issues

- Prediction of Stiffness, Damage Initiation, and Failure Loads for Complex Structure
  - Increased Test Cost and Complexity
    - Little Statistical Information
    - More Uncertainty in Loading, Boundary Conditions
- Reliability-Based Design
  - Characterization of Environment
    - Loads, Temperature, Moisture, Damage
  - Very High Reliability Required (interested in extremes/tails)

DARPA

NAVAL AVIATION SYSTEMS TEAM

Understanding and managing uncertainty is an integral part of the AIM Structural Property Prediction approach.

The Structural Property Prediction tools must:

- Present clear traceability to data input pedigree
  - Redundant methods for data checking
- Identify when models are out of their predictive bounds, validated bounds
- Have stochastic definition of important Input and Output properties
- Possess a simple automated user interface to minimize I/O errors
- Undergo extensive validation to identify errors

Practical Aspects of Managing Uncertainty

- Indirect property measurement often required
- Testing expense and/or history can limit data populations
- Assumptions necessary to develop efficient models
- Focus on significant inputs (can vary from case to case)
  - Use sensitivity studies to identify criticality of factors

- Input Material Properties
  - Test methods – accuracy, repeatability, errors
  - Distribution – data correlation, population, inferred properties

- Modeling
  - Accuracy of physical models
  - Idealization assumptions
  - Interpolation, extrapolation of input datasets

- Output values
  - Interpolation, extrapolation of output datasets
  - Post processing of data

Coupon Failure Modeling Errors and Uncertainties

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Lamina Stiffness/ Thermal Properties (CCA and/or Empirical)	Variation in all fiber and resin moduli, Poisson's ratio, and CTE properties. Test uncertainties such as specimen misalignment, load/displacement measurement	Unmeasurable Constituent Properties (transverse fiber modulus, etc.) Interphase effects	CCA: Use of model outside of bounds.(e.g., woven 3D preform) Empirical: Extrapolation beyond test data (fiber volumes, temperatures, etc.)	CCA: I/O errors, code bugs Empirical:Testing machine not calibrated. Poor specimen preparation; poor strain measurement techniques.
Laminate Stiffness Calculation (CLPT)	Variations in ply-thickness, ply angles, etc.	Assumes thin plate with no shear deformation, material or geometric nonlinearity, or significant transverse strains.	Use of model outside bounds for items listed under Epistemic uncertainty)	I/O errors (ply thickness, material, layup definition), code bugs
Stress-Free Temps/ Residual Curing Strain Input (COMPRO)	Many parameters can affect residual stress: local fiber volume fraction, …	Micro-stresses are considered to be independent of meso-stresses; there are few independent measurements of residual stress.	The formulation is believed to be most accurate when the cure cycle temperature is higher than the Tg. Otherwise the residual stress calculated can be an overestimate.	Errors in material property definition, errors in coding, errors in integrating process and structural models.
Coupon Geometry and Load/BC Input (COMPRO, User-defined, Empirical)	Cured ply thickness variations, specimen dimensional tolerances, specimen curvatures due to residual stress/strain			Errors in Coupon Geometry Definition or Improper Idealization of Loading or Boundary Conditions

Coupon Failure Modeling Errors and Uncertainties

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Laminate/Lamina Stress/Strain Field (ANSYS or ABAQUS)	All material and geometry variables listed previously.	Unknown or highly-variable geometry (of fillets, etc.) near geometric free edge singularities.	Mesh convergence - generally converged to within 5%, tends to favor slight overprediction	I/O errors, bugs in UMAT or APDL coding for mesh convergence, thermal and mechanical strain superposition, and failure value extraction.
Constituent Stress/Strain Calculation (UC-FEA or PASS)	Variation in fiber volume, packing arrangements, fiber and matrix moduli, Poisson's ratios, CTEs..	Unknown local variations of items listed under Aleatory uncertainty. No direct measurement of certain fiber properties. Unknown effect of interphase.	UC-FEA: Use of model outside of bounds (eg different product form). Mesh convergence. PASS – Assumes averaging of constituent stresses/strain.	I/O errors, code bugs Testing and measurement errors in input constituent properties (listed under aleatory uncertainties)
Critical Constituent Failure Property Input (Empirical or Empirical+Analysis)	Specimen variation; Test uncertainties such as specimen misalignment, load/displacement measurement		Often measured indirectly from lamina/laminate testing. Conversion to constituent values by analysis is subject to all analytical errors previously listed. Errors minimized due to simple coupon geometries.	Testing machine not calibrated. Poor specimen finish, poor alignment in grips. Poor strain measurement techniques. I/O and coding errors in analytical procedures.
Constituent Failure (Damage Initiation) Calculation	Variations in critical failure parameters and constituent stress strain field (from items above)		Use of criteria outside of theoretical or validated bounds.	Inappropriate choice of failure criteria (by user or tool). Code bugs.

Workshop Topics of Interest

- Methodology for identifying uncertainties, characterizing them, and documenting them productively.
- Case studies which demonstrate success in handling uncertainty and pitfalls to avoid.
- Recommended methodologies for handling a mix of experimental and analytical data.

Workshop Topics of Interest

- Issues in developing probabilistic models from sparse data (such as 5 tests each at 3 to 5 temperatures or 5 tests on each of 3 to 5 batches).

  Issues in use of these models in design of systems that demand high reliability.

  Ideal and acceptable approaches to this issue

  Compute intensive and non-compute intensive situation of numerical simulations

Workshop Topics of Interest

- Model validation approaches for deterministic and stochastic models in the context of limited experiments to verify/augment model results.
- Technologies used in other domains that have been most successful in the treatment of uncertainties comparable to AIM uncertainty treatment objectives.

Uncertainty Definition

- "Uncertainty" is used to encompass a multiplicity of concepts
  - Used to describe incomplete information
  - Used to describe to variability
  - Uncertainty may arise because of simplification or approximations introduced to analyze the information cognitively or computationally more tractable
  - Uncertainty may refer to uncertainty in our decisions

Uncertainty Definition and Use

- It is necessary to distinguish between different types and sources of uncertainty so that they can be treated differently
- Probability is considered as an appropriate way to express some of the above uncertainties

- Uncertainty analysis could be the framework of arriving at design allowable

Propagation Interpretation

- All the following refer to the same process
  - Propagation of Uncertainty
  - Error Propagation
  - Variance Propagation
- $y = F(X)$
  - Given the uncertainty in X, compute the uncertainty in y

Propagation Interpretation

- F(x) Representation
  - Surrogate Models
    - Taylor Series for low order statistics
    - Response Surface
  - Actual Models
    - Single or multiple models connected in the form of a network

Functional Models

- Some closed form but mostly finite element based codes - commercial and in-house proprietary
- linear and nonlinear analysis
- special purpose material model libraries
- compute intensive nature
  - solution time problem dependent

Composite Materials Domain

- Uncertainties are introduced at all levels
  - Fiber, Resin and the interface
  - Prepreg
  - Lamina
  - Laminate
  - Sub-component/Component
  - Structure
  - Manufacture and use conditions
- Modeling of material processing is critical

Probability Computation Technologies

- Simulation Based
  - Monte Carlo simulation and variations
- Global Response Surface
  - Full and Fractional factorial designs based on DOE technology
- Structural Reliability Methods
  - First order Reliability Methods and its many variants

Challenges
Mathematical Foundations

- Quantifying the Error bands and/or confidence interval
  - Database with data of different pedigree
    - data from analytical models, test results, and from past experience database of same or similar material
  - Computationally tractable approaches
    - Simulation within a simulation can be expensive for compute intensive models

Challenges
Mathematical Foundations

- Extrapolation (tail sensitivity- impact on the design of highly reliable systems)
  - Distribution approximations from small sample sizes
  - sample sizes are typically 5 to 10 for each treatment
  - Due to large treatment combinations, large number of samples are involved and pooling is resorted to

Challenges
Mathematical Foundations

- Deterministic and stochastic model validation and/or updating
  - development of technologies for focused testing with model update/validation as a goal
    - consideration of experimental errors
    - limited but high value added tests

Technology Basis

- Probabilistic Analysis civil engineering books
  - Benjamin and Cornell
  - Ang and Tang
  - Ditlevsen and Madsen
- Statistics, DOE, Response Surface books
  - Box and Hunter
- Reliability Engineering books
  – Kapur
- Robust Engineering books
  – Taguchi, Padke

Technology Basis

- Research reports
  - PRA from Nuclear Industry
  - DOE National Laboratory
  - EPA Risk Analysis
- Technologies from other disciplines would be helpful
  - control systems, operations Research, artificial intelligence, network Theories, investment banking